

# Evidence for an axion-like particle from PKS 1222+216?

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## ABSTRACT

The surprising discovery by MAGIC of an intense, rapidly varying very high energy ( $E > 50$  GeV) emission from the flat spectrum radio quasar PKS 1222+216 represents a challenge for all interpretative scenarios. Indeed, in order to avoid absorption of  $\gamma$  rays in the dense ultraviolet radiation field of the broad line region (BLR), one is forced to invoke the existence of a very compact ( $r \sim 10^{14}$  cm) emitting region at a large distance ( $R > 10^{18}$  cm) from the jet base. We present a scenario based on the standard blazar model for PKS 1222+216 where  $\gamma$  rays are produced close to the central engine, but we add the new assumption that inside the source photons can oscillate into axion-like particles, which are a generic prediction of many extensions of the Standard Model of elementary particle interactions. As a result, a considerable fraction of photons can escape absorption from the BLR much in the same way as they largely avoid absorption from extragalactic background light when propagating over cosmic distances. We show that observations can be explained in this way for reasonable values of the model parameters, and in particular we find it quite remarkable that the most favourable value of photon-ALP coupling happens to be the same in both situations. An independent laboratory check of our proposal can be performed by the planned upgrade of the ALPS experiment at DESY.

**Key words:** radiation mechanisms: non-thermal —  $\gamma$ -rays: theory — galaxies: individual: PKS 1222+216

## 1 INTRODUCTION

Blazars dominate the extragalactic  $\gamma$ -ray sky, both at high energy ( $> 100$  MeV) and at very high energy (VHE) ( $> 50$  GeV). Their powerful non-thermal emission, spanning the entire electromagnetic spectrum, is produced in a relativistic jet pointing toward the Earth. The spectral energy distribution (SED) shows two well defined “humps”. The first one – peaking somewhere between the IR and the X-ray bands – derives from the synchrotron emission of relativistic electrons (or pairs) in the jet. The origin of the second component which exhibits a maximum at  $\gamma$ -ray energies is more debated. Leptonic models attribute it to the inverse Compton emission of the same electrons responsible for the lower energy bump. Hadronic models, instead, assume that the  $\gamma$  rays are the leftover of reactions involving relativistic hadrons. Blazars are further divided into two broad groups, BL Lac objects and flat spectrum radio quasars (FSRQs). BL Lacs are defined by the weakness (or even absence) of thermal features (most notably broad emission lines) in their optical spectra. This evidence leads to the common belief that the nuclear region of BL Lacs, where the jet forms and accelerates is rather poor of soft photons. On the contrary, FSRQs display luminous broad ( $v > 1000$  km s<sup>−1</sup>) emission lines, indicating the ex-

istence of photo-ionized clouds rapidly rotating around the central black hole and organized in the so-called broad line region (BLR).

Besides their importance for the study of the structure and functioning of relativistic jets, growing interest for blazars is motivated by the use of their intense  $\gamma$ -ray beam as a probe of the extragalactic background light (EBL) (see e.g. Aharonian et al. 2006) and the intergalactic magnetic fields (see e.g. Neronov & Vovk 2010, Tavecchio et al. 2010) and – even more fundamentally – for the study of new physical phenomena beyond the Standard Model (SM) of elementary particle interactions and even quite radical departures from conventional physics such as violation of Lorentz invariance (for a review, see Liberati & Maccione 2009). Concerning the possible evidence for new elementary particles, particular importance is played by axion-like particles (ALPs) – namely very light spin-zero bosons  $a$  characterized by a two-photon coupling  $a\gamma\gamma$  – which are a generic prediction of many extensions of the SM (for a review, see Jaekel & Ringwald 2010). In the presence of an external magnetic field, the  $a\gamma\gamma$  coupling gives rise to the phenomenon of photon-ALP oscillations (conversion), quite similar to oscillations of massive neutrinos of different flavour. Within the present context, photon-ALP oscillations can drastically alter the propagation of hard photons of energy  $E$  from a blazar to us. Two different scenarios have been proposed. One – called DARMA – contemplates photon-ALP oscillations  $\gamma \rightarrow a \rightarrow \gamma$  as taking

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place in intergalactic space (De Angelis et al. 2007, De Angelis et al. 2009, Mirizzi & Montanino 2009, De Angelis et al. 2011 [D2011]) where a large-scale magnetic field in the nG range is supposed to exist, which is consistent with present upper bounds (Kronberg 1994, Blasi et al. 1999, Grasso & Rubinstein 2001) and AUGER results (Abreu et al. 2010). Alternatively, the conversion  $\gamma \rightarrow a$  can occur inside the blazar jet whereas the re-conversion  $a \rightarrow \gamma$  can happen in the Milky-Way (Simet et al. 2008). Needless to say, also both options can be realized at once (Sanchez-Conde et al. 2009). In either case, what we are used to simply regard as a *photon* behaves for some time as a “true photon” and for some time as an ALP. Now, “true photons” can disappear from the beam along their way to us through the  $\gamma\gamma \rightarrow e^+e^-$  scattering with low-energy photons of the EBL while ALPs propagate unaffected by the EBL, since the process  $a\gamma \rightarrow \gamma$  is kinematically forbidden. As a result, owing to photon-ALP oscillations the effective photon optical depth  $\tau_{\text{eff}}(E)$  gets smaller, and even a tiny decrease entails a large enhancement of the photon survival probability  $P_{\gamma \rightarrow \gamma}(E)$  as compared with conventional physics since

$$P_{\gamma \rightarrow \gamma}(E) = \exp[-\tau_{\text{eff}}(E)]. \quad (1)$$

In addition, because the EBL dimming increases with  $E$  whereas the photon-ALP oscillations alone are  $E$ -independent, the resulting observed blazar spectra become harder than expected and in particular the “ $\gamma$ -ray horizon” gets considerably enlarged.

Coming back to blazar observations, the recent evidence of VHE emission by FSRQs poses a quite serious challenge. As stressed above, the surrounding of the inner jet in FSRQs is rich of optical-UV photons emitted by the BLR, necessarily implying a huge optical depth for  $\gamma$  rays above 10–20 GeV (see e.g. Liu & Bai 2002, Tavecchio & Mazin 2009 [TM2009], Poutanen & Stern 2011). Therefore, the observation of some FSRQs at TeV energies raised great surprise (Albert et al. 2008, Aleksic et al. 2011a, Wagner & Behera 2010). Moreover, the detection of an intense VHE emission from PKS 1222+216 (Aleksic et al. 2011a) observed by MAGIC to double its flux in only about 10 minutes – thereby flagging the extreme compactness of the emitting region – is very difficult to fit within the standard model (Tavecchio et al. 2011 [T2011]).

So far, the only possibility to solve the apparent contradiction between the detection of the intense and relatively hard flux and the rapid variation appears to invoke the existence of very small ( $r \sim 10^{14}$  cm) emitting regions beyond the BLR ( $R \sim 10^{18}$  cm), that is at a large distance from the central engine.

Our proposal to explain the observations of PKS 1222+216 assumes the validity of the standard model for photon production but we add the new assumption that photon-ALP oscillations take place inside the source in such a way that a considerable fraction of photons can leave it, indeed much in the same fashion that a considerable fraction of photons emitted by blazars avoid EBL absorption in intergalactic space. We envisage that the  $\gamma \rightarrow a$  conversion occurs before most of the photons reach the BLR. Accordingly, ALPs traverse this region unimpeded and outside it the re-conversion  $a \rightarrow \gamma$  takes place either in the same magnetic field of the source or in that of the host galaxy. So, our proposal differs from any previously considered one.

The plan of the paper is as follows. The mechanism of photon-ALP oscillations is reviewed in general terms in §2. Our proposed model for PKS 1222+216 is described in §3 and its results are presented in §4. Finally, in §5 we compare our model with the two-blob scenario developed in [T2011] to explain the same observations and we discuss some features of the model presented in this Letter.

## 2 PHOTON-ALP OSCILLATIONS

We consider in the following a monochromatic photon beam of energy  $E$  travelling along the  $y$  direction from the centre of the source to us. In this section we use natural units, in which  $c = \hbar = 1$ .

Below, we cursorily describe the mechanism whereby photon-ALP oscillations occur in the beam propagating in a generic ionized and magnetized medium where photons can be absorbed but ALPs can not (a very detailed account can be found in [D2011]<sup>1</sup>).

Basically, the SM is enlarged so as to include an ALP which is described by the Lagrangian

$$\mathcal{L}_{\text{ALP}} = \frac{1}{2} \partial^\mu a \partial_\mu a - \frac{1}{2} m^2 a^2 + \frac{1}{M} \mathbf{E} \cdot \mathbf{B} a, \quad (2)$$

where  $m$  is the ALP mass and  $M$  is a constant with the dimension of an energy. More specifically, it is generally supposed that  $m < 1$  eV, and the CAST experiment (Arik et al. 2009) sets the robust bound  $M > 1.1 \times 10^{10}$  GeV for  $m < 0.02$  eV while from the absence of  $\gamma$  rays coming from SN 1987A the stronger bound  $M > 10^{11}$  GeV has been derived for  $m < 10^{-10}$  eV even if with a large uncertainty (Brockway et al. 1996, Grifols et al. 1996). Clearly the last term in Eq. (2) gives rise to the  $a\gamma\gamma$  coupling mentioned above. Note that because of the specific form of this coupling  $\propto \mathbf{E} \cdot \mathbf{B}/M$  only the component of  $\mathbf{B}$  in the  $x - z$  plane  $\mathbf{B}_T$  couples to  $a$ , and in addition all physical results depend only on the combination  $B_T/M$ .

The first point that deserves concern is that in the approximation  $E \gg m$  the beam propagation equation becomes (Raffelt & Stodolski 1988)

$$\left( i \frac{d}{dy} + E + \mathcal{M}(y) \right) \begin{pmatrix} A_x(y) \\ A_z(y) \\ a(y) \end{pmatrix} = 0, \quad (3)$$

where  $A_x(y)$  and  $A_z(y)$  are the two photon linear polarization amplitudes along the  $x$  and  $z$  axis, respectively,  $a(y)$  denotes the ALP amplitude and  $\mathcal{M}$  represents the photon-ALP mixing matrix, whose explicit form is (Mirizzi et al. 2005)

$$\mathcal{M}(y) = \begin{pmatrix} \Delta_{xx} & 0 & \Delta_{a\gamma}^x \\ 0 & \Delta_{zz} & \Delta_{a\gamma}^z \\ \Delta_{a\gamma}^x & \Delta_{a\gamma}^z & \Delta_{aa} \end{pmatrix}. \quad (4)$$

Denoting by  $\omega_{\text{pl}}(y)$  the plasma frequency – related to the electron number density  $n_e(y)$  by  $\omega_{\text{pl}}(y) \simeq 3.69 \times 10^{-11} \sqrt{n_e(y)/\text{cm}^{-3}} \text{ eV}$  – by  $\lambda_\gamma(E, y)$  the photon mean free path and by  $B_x(y)$  and  $B_z(y)$  the  $x$  and  $z$  components of the magnetic field  $\mathbf{B}(y)$ , the various  $\Delta$  terms are  $\Delta_{xx} = \Delta_{zz} = -\omega_{\text{pl}}^2(y)/2E + i/2\lambda_\gamma(E, y)$ ,  $\Delta_{a\gamma}^x = B_x(y)/2M$ ,  $\Delta_{a\gamma}^z = B_z(y)/2M$  and  $\Delta_{aa} = -m^2/2E$ . A very remarkable fact is that Eq. (3) is a Schrödinger-like equation with  $y$  playing the role of time, and so the relativistic beam in question can formally be treated as a three-level non-relativistic unstable quantum system with non self-adjoint Hamiltonian  $H(y) = -[E + \mathcal{M}(y)]$ . This circumstance allows us to describe the behaviour of the beam by non-relativistic quantum mechanics. Moreover, we denote by  $U(y, y_0)$  the transfer matrix, namely the solution of Eq. (3) with initial condition  $U(y_0, y_0) = 1$ . Actually, we assume that initially the beam is fully made of photons whose polarization is unknown to a considerable extent, so that it is safe to regard the beam initially as unpolarized. Therefore, it must be described by the (generalized) density matrix  $\rho(y)$

<sup>1</sup> Although the results presented in this paper are all correct, Eqs. (104) and (134) are written incorrectly and their denominator should be dropped, so that they have to look like Eq. (48).

which – thanks to the above analogy – obeys the Von Neumann-like equation

$$i \frac{d\rho}{dy} = \rho \mathcal{M}^\dagger - \mathcal{M} \rho \quad (5)$$

associated with Eq. (3). Then it follows that even if  $\mathcal{M}^\dagger \neq \mathcal{M}$  the solution of Eq. (5) is given by  $\rho(y) = U(y, y_0) \rho(y_0) U^\dagger(y, y_0)$ , and since in the  $\gamma$ -ray band the photon polarization cannot be measured the photon survival probability after a distance  $y$  for the beam initially in the state unpolarized state  $\rho_{\text{unp}}$  is

$$P_{\gamma \rightarrow \gamma}(E, y) = \sum_{i=x,z} \text{Tr}(\rho_i U(y, 0) \rho_{\text{unp}} U^\dagger(y, 0)), \quad (6)$$

where  $\rho_x$  and  $\rho_z$  denote the linearly polarized states along  $x$  and  $z$ , respectively.

Consider now the particular case in which no absorption is present and  $\mathbf{B}$  is homogeneous. Then we can choose the  $z$  axis along  $\mathbf{B}_T$  so that  $B_x = 0$ . In this case the photon-ALP conversion probability can be computed exactly and reads

$$P_{0,\gamma \rightarrow a}(E, y) = \left( \frac{B_T}{M \Delta_{\text{osc}}} \right)^2 \sin^2 \left( \frac{\Delta_{\text{osc}} y}{2} \right), \quad (7)$$

where we have set  $\Delta_{\text{osc}}^2 \equiv [(m^2 - \omega_{\text{pl}}^2)/(2E)]^2 + (B_T/M)^2$ . Hence, we see that for  $E \gg E_*$  with  $E_* \equiv |m^2 - \omega_{\text{pl}}^2| M / 2B_T$  the *strong-mixing regime* takes place, in which the photon-ALP conversion probability becomes maximal and energy-independent. Another important consequence of the strong-mixing regime is that the general mixing matrix  $\mathcal{M}(y)$  simplifies since the terms  $\omega_{\text{pl}}^2(y)/2E$  and  $m^2/2E$  should be discarded.

### 3 A MODEL FOR PKS 1222+216

We now proceed to build up our model for PKS 1222+216.

In the first place we need the knowledge of the relevant physical parameters. We assume a disk luminosity  $L_D \simeq 5 \times 10^{46}$  erg s<sup>-1</sup>, a radius of the BLR  $R_{\text{BLR}} \simeq 7 \times 10^{17}$  cm ([T2011]), and standard values of the BLR cloud number density  $n_c \simeq 10^{10}$  cm<sup>-3</sup> and temperature  $T_c \simeq 10^4$  K (see e.g. [TM2009]). Since the filling factor of the clouds is small, the average electron number density  $n_e$  relevant for the beam propagation is much smaller than  $n_c$ . Models attributing the confinement of the clouds to a hot  $T_e \simeq 10^{7-8}$  K external medium in pressure equilibrium with the clouds yield  $n_e \simeq 10^{6-7}$  cm<sup>-3</sup> (see e.g. Krolik et al. 1981). However, the presence of such a hot confining medium is disfavored by the lack of the necessarily expected bright X-ray emission. So, an extra contribution to the pressure confining the BLR clouds is expected e.g. from the magnetic field (see e.g. Netzer 2008). What matters for us is that  $n_e$  gets considerably reduced, and for definiteness we take  $n_e \simeq 10^4$  cm<sup>-3</sup>. At any rate, since we are working in the strong-mixing regime the photon survival probability is *unaffected* by  $n_e$ , which only enters  $E_*$ . What about the magnetic field  $\mathbf{B}$ ? Unfortunately, its strength and geometry in the innermost region of an AGN are very poorly known and in first approximation  $\mathbf{B}$  can be taken as uniform. A possible estimate of its strength can be derived by assuming equipartition between magnetic and gas pressure, leading to  $B \simeq 1$  G (see e.g. Rees 1987). Thus, we assume  $B \simeq 1$  G from the emission region out to  $R_{\text{BLR}}$ . But since we need to follow the beam until it exits from the host galaxy we have also to provide a description of  $\mathbf{B}$  beyond the BLR. Due to the fact that the BLR is surrounded by ionized gas with a smoothly declining density, it looks natural to suppose that the  $\mathbf{B}$  field lines are frozen-in, so that

flux conservation entails  $B(R) \simeq (R/R_{\text{BLR}})^{-2}$  G. Furthermore, FSRQs are hosted by elliptical galaxies, whose  $\mathbf{B}$  is very poorly known. Nevertheless, it has been argued that supernova explosions and stellar motion give rise to a turbulent  $\mathbf{B}$  ranging from about 10  $\mu$ G at the centre to about 1  $\mu$ G at 10 kpc (Moss & Shukurov 1996). Because of such a small gradient of  $B$  across the galaxy and its associated uncertainty, we will take  $B \simeq 5 \mu$ G throughout the galaxy.

We start by computing the optical depth  $\tau(E)$  of the beam photons according to conventional physics, which amounts to consider only the process  $\gamma\gamma \rightarrow e^+e^-$ . We follow the same procedure developed in [TM2009], to which we refer the reader for a full description of the method. The optical depth is derived using the detailed spectrum emitted by the photo-ionized BLR clouds. The result is plotted as the blue dashed line in Fig. 1.

Next, we turn our attention to the situation in which photon-ALP oscillations occur in the beam. Owing to the varying physical properties in the space traversed by the beam, we perform an independent analysis of three regions:

- The inner part of the blazar, namely from the centre to  $R_{\text{BLR}}$ , where  $\mathbf{B}$  is supposed to be uniform.
- The region surrounding the BLR, where  $\mathbf{B}$  is assumed to decrease like  $R^{-2}$  until it reaches the strength of the galactic  $\mathbf{B}$  at the galactocentric value  $R_* \simeq 10^2$  pc.
- The galactic region from  $R_* \simeq 10^2$  pc to  $R_{\text{host}} \simeq 10$  kpc where  $\mathbf{B}$  has a constant strength but a turbulent nature.

We begin from the first item. The most important issue to settle is to find out the actual value of  $E_*$  above which the strong-mixing regime sets in for the assumed values of the electron density and of the strength of  $\mathbf{B}$ . To this end, it is useful to rewrite  $E_*$  in the form

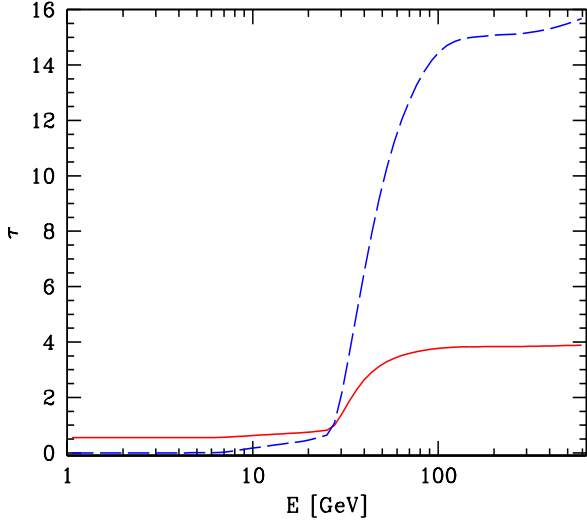
$$E_* \simeq 0.26 \times 10^{22} |m^2 - \omega_{\text{pl}}^2| \left( \frac{G}{B_T} \right) \left( \frac{M}{10^{11} \text{ GeV}} \right) \text{ eV}^{-1}. \quad (8)$$

For  $n_e \simeq 10^4$  cm<sup>-3</sup> we get  $\omega_{\text{pl}} \simeq 3.69 \times 10^{-9}$  eV. Moreover, we have chosen  $B \simeq 1$  G but we do not know its direction, which is quite likely to change with the distance from the centre. Because the photon-ALP oscillation vanishes if  $\mathbf{B}$  is along the beam while it is maximal for  $\mathbf{B}$  normal to the beam, we suppose that  $\mathbf{B}$  is on average at an angle of 45° with the beam direction. Therefore we have  $B_T \simeq 0.7$  G. Finally, the bound  $M > 1.1 \times 10^{10}$  GeV certainly holds. So, putting everything together, from Eq. (8) we get  $E_* \simeq 0.2$  MeV under the assumption that  $m < \omega_{\text{pl}}$  [D2011]. This is a welcome conclusion, because we do not run the risk that photon-ALP oscillations affect X-ray observations of FSRQs while they do affect their observations performed both by Fermi/LAT and by Cherenkov telescopes like MAGIC.

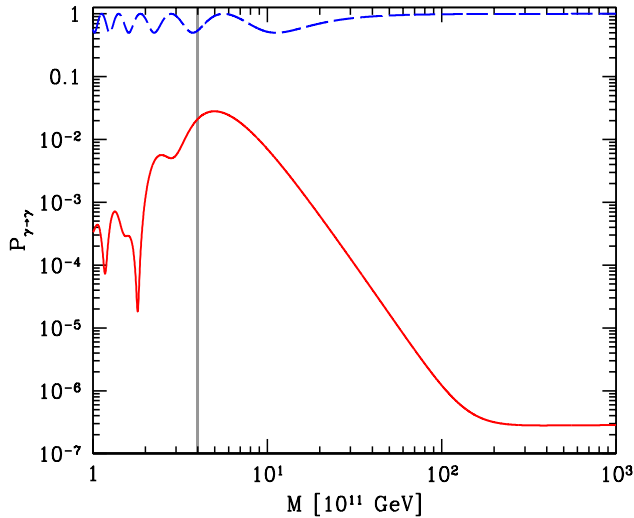
Moreover, we get  $\lambda_\gamma(E) = R_{\text{BLR}}/\tau(E)$  for  $R < R_{\text{BLR}}$ . At this point, following [D2011] the calculation of the transfer matrix – which we denote by  $U_1(R_{\text{BLR}}, 0)$  – is in the present case straightforward. As a consequence, the beam state at  $R_{\text{BLR}}$  is  $\rho_{\text{BLR}} = U_1(R_{\text{BLR}}, 0) \rho_{\text{unp}} U_1^\dagger(R_{\text{BLR}}, 0)$ .

Let us next turn our attention to the second item. Remarkably enough, for  $B(R) \simeq (R/R_{\text{BLR}})^{-2}$  G Eq. (3) can be solved exactly – in this region absorption can safely be neglected – and we denote by  $U_2(R_*, R_{\text{BLR}})$  the corresponding transfer matrix. So, the beam state at  $R_*$  is  $\rho_{R_*} = U_2(R_*, R_{\text{BLR}}) \rho_{\text{BLR}} U_2^\dagger(R_*, R_{\text{BLR}}) = U_2(R_*, R_{\text{BLR}}) U_1(R_{\text{BLR}}, 0) \rho_{\text{unp}} U_1^\dagger(R_{\text{BLR}}, 0) U_2^\dagger(R_*, R_{\text{BLR}})$ .

Finally, we address the third item. According to Moss & Shukurov (1996), we model  $\mathbf{B}$  in the host elliptical galaxy as a domain-like structure, with strength 5  $\mu$ G and domain size equal to 150 pc. In this case the beam propagation can be computed ex-



**Figure 1.**  $\gamma\gamma$  optical depth as a function of energy for photons propagating in the BLR of PKS 1222+216 (blue dashed line), calculated within conventional physics as in [T2009]. The red solid line shows the effective optical depth assuming photon-ALP conversion. See text for details.



**Figure 2.** Photon survival probability  $P_{\gamma \rightarrow \gamma}$  at 1 GeV (blue dashed line) and at 200 GeV (red solid line) as a function of the inverse  $a\gamma\gamma$  coupling constant  $M$ . The gray vertical line indicates the value used in the model,  $M = 4 \times 10^{11}$  GeV.

actly as in [D2011] without absorption, and the resulting transfer matrix is denoted by  $U_3(R_{\text{host}}, R_*)$ . However, this last effect turns out to give a very small contribution. Thus, by replacing  $\mathcal{U}(\dots) \rightarrow U_3(R_{\text{host}}, R_*) U_2(R_*, R_{\text{BLR}}) U_1(R_{\text{BLR}}, 0)$  in Eq. (134) of [D2011] and going through the same steps we find the photon survival probability  $P_{\gamma \rightarrow \gamma}(E)$  from PKS 1222+216 to us. We stress that this conclusion ultimately rests upon the application of Eq. (6).

## 4 RESULTS

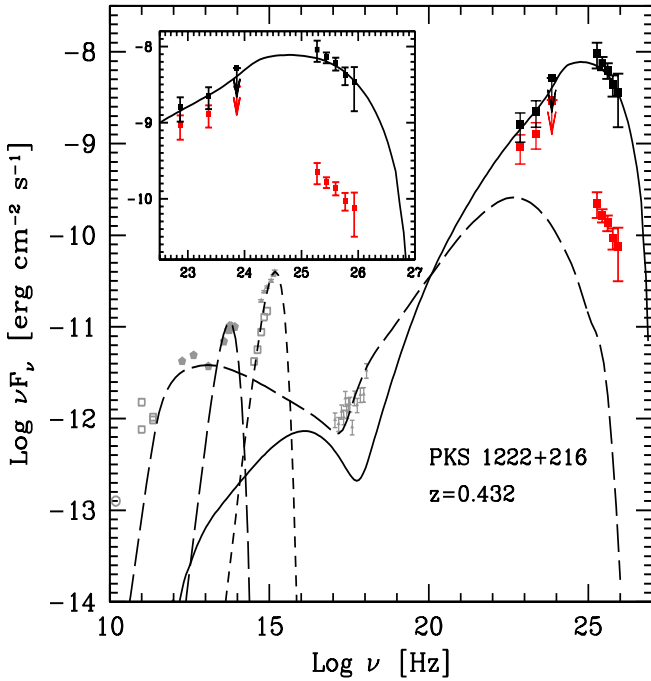
Our source has been observed by *Fermi*/LAT in the energy range 0.3 – 3 GeV and by MAGIC in the band 70 – 400 GeV. Therefore we focus our attention on the energies  $E = 1$  GeV and  $E = 200$  GeV as representative of the two kinds of measurements. We show in Fig. 2  $P_{\gamma \rightarrow \gamma}(E)$  at these energies as a function of  $M$ , namely the inverse  $a\gamma\gamma$  coupling constant: The blue dashed line corresponds to 1 GeV while the red solid line to 200 GeV. We see that  $P_{\gamma \rightarrow \gamma}(200 \text{ GeV})$  reaches its maximum close to  $M = 4 \times 10^{11}$  GeV, which is evidently our most favourable case. Since at 1 GeV no photon absorption occurs, on the basis of Eq. (7) we expect an oscillatory behaviour, even though outside  $R_{\text{BLR}}$   $B$  first decreases and then has a random domain-like structure. Moreover, since the oscillation wavelength is  $L_{\text{osc}} = 2\pi M/B$  it has to increase with  $M$ . Both features are reproduced by the blue dashed line. The behaviour of the red solid line is more difficult to understand in intuitive terms due to the presence of a strong photon absorption. Certainly beyond a certain value of  $M$  photon-ALP oscillations become ineffective and absorption dominates: we see from the figure that this is indeed the case for  $M > 10^{13}$  GeV. For smaller values of  $M$  photon-ALP oscillations become efficient, but when they are very efficient – and this occurs fairly soon – some ALPs are re-converted back into photons before leaving the BLR, thereby getting absorbed. This explains why  $P_{\gamma \rightarrow \gamma}(E)$  peaks at some value of  $M$ .

In order to get deeper insight into the physical relevance of our result, using Eq. (1) from  $P_{\gamma \rightarrow \gamma}(E)$  we obtain the effective optical depth  $\tau_{\text{eff}}(E)$  – as evaluated for  $M = 4 \times 10^{11}$  GeV – which is represented by the red solid line in Fig. 1. The effect of the photon-ALP oscillations on the beam propagation can be readily appreciated. Indeed, photon-ALP oscillations lead to a drastic reduction of the optical depth in the optically thick range: in the MAGIC band it is almost constant  $\tau_{\text{eff}} \simeq 4$ , corresponding to a survival probability of about 2% as it is evident also from Fig. 2. On the contrary, in the optically thin region below  $\sim 30$  GeV, the optical depth in the presence of the photon-ALP conversion is *larger* than the standard one, which instead goes rapidly to zero below 10 GeV. This behaviour can be simply understood: a fraction around 40% of the  $\gamma$  rays originally emitted by the source and converted into ALPs do not reconvert to photons, therefore leading to a reduction of the observed photon flux.

Let us now explicitly address the impact of our model for the SED of PKS 1222+216, which is illustrated in Fig. 3. The red points at high energies are the *Fermi*/LAT and MAGIC *EBL-deabsorbed* data around the epoch of the VHE detection taken from Aleksic et al. 2011a (see [T2011] for details and references). As far as our model is concerned, the intrinsic flux  $F_{\text{int}}(E)$  is clearly related to the EBL-deabsorbed observed one  $F_{\text{obs}}(E)$  by  $F_{\text{int}}(E) = F_{\text{obs}}(E)/P_{\gamma \rightarrow \gamma}(E) = F_{\text{obs}}(E) \exp[\tau_{\text{eff}}(E)]$ . Application of this relation to the red points yields the corresponding black points in Fig. 3. We see that the black points corresponding to *Fermi*/LAT and MAGIC observation describe a Compton bump peaking at  $\sim 50$  GeV, similar to that of BL Lacs.

## 5 DISCUSSION AND CONCLUSIONS

We find it instructive to compare our proposal with the one presented in [T2011], where the SED comprising the red  $\gamma$ -ray data is reproduced by a model consisting in two active compact regions, one responsible for the emission from IR to X-rays and the other,



**Figure 3.** SED of PKS 1222+216 around the epoch of the MAGIC detection. Red points at high and very high energy are the spectrum recorded by *Fermi*/LAT and MAGIC (EBL-corrected). The black points represent the same data once corrected for the photon-ALP oscillation effect. The curves show the result of a standard leptonic emission model assuming two regions located inside the BLR responsible for the emission at low and high energy, respectively. The gray data points below  $10^{20}$  Hz are irrelevant for the present discussion (details can be found in [T2011]).

very compact, accounting from the rapidly varying  $\gamma$ -ray emission. The latter region is assumed to lie at  $R > 10^{18}$  cm., namely beyond the BLR, so as to avoid the resulting huge photon absorption. We refer to [T2011] for a full discussion of the problems and the detailed description of the model. Briefly, each region is specified by its size  $r$ , magnetic field  $B$ , bulk Lorentz factor  $\Gamma$ , electron normalization  $K$ , minimum, break and maximum Lorentz factors  $\gamma_{\min}$ ,  $\gamma_b$ ,  $\gamma_{\max}$  and slopes  $n_1$ ,  $n_2$ . The electrons radiate through synchrotron and inverse Compton emission (considering both the internally produced synchrotron radiation and the external radiation of the BLR). For the larger region we use the parameters reported in [T2011] while for the compact  $\gamma$ -ray emitting region the model is specified by the following parameters:  $r = 2.2 \times 10^{14}$  cm,  $B = 0.025$  G,  $\Gamma = 17.5$ ,  $K = 4.1 \times 10^9$ ,  $\gamma_{\min} = 1.5 \times 10^3$ ,  $\gamma_b = 10^5$ ,  $\gamma_{\max} = 4 \times 10^5$  and slopes  $n_1 = 2.1$ ,  $n_2 = 4.2$ . As discussed in [T2011] the relative position of the two regions is not relevant for the emission properties.

We remark that the emission model just discussed is merely an example, and different and possibly more realistic scenarios can be constructed. The key point we want to make is that with the photon-ALP oscillation mechanism at work the emission can well originate inside the BLR just like in conventional models.

Needless to say, our scenario naturally applies also to the other FSRQs detected at VHE like 3C279 and PKS 1510-089 (Albert et al. 2008, Aleksic et al. 2011b, Wagner 2010), although these cases appear less problematic for the external emission scenario due to the absence of evident rapid ( $t < 1$  day) variability.

Finally we would like to mention a possible test of the proposed model. Because photon-ALP oscillations can mitigate – but not completely avoid – the  $\gamma$ -ray absorption inside the BLR, a natural prediction is that at the optically-thin/optically thick transition around 30 GeV (in the source frame) the spectrum should display a feature. So, the absence of such a feature would be hard to explain in our model but would directly support scenarios in which the emission occurs outside the BLR.

We find it quite tantalizing that precisely the most favourable value  $M \simeq 4 \times 10^{11}$  GeV for the effect considered in this Letter coincides with the most favourable value in the DARMA scenario that enlarges the “ $\gamma$ -ray horizon” and provides a natural solution to the cosmic opacity problem [D2011] (also a very small ALP mass  $m < 10^{-9} - 10^{-10}$  eV is common to both models). Yet, we have neglected photon-ALP oscillations in intergalactic space – which would increase  $P_{\gamma \rightarrow \gamma}(E)$  – in order to put ourselves in the less optimistic case. Remarkably enough, an independent laboratory check of our proposal can be performed by the planned upgrade of the ALPS experiment at DESY.

A much more detailed presentation of the matter reported here will soon appear.

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